



# Different parameters affecting the rate of evaporation and condensation on passive solar still – A review

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## ABSTRACT

Scarcity for water exists in many countries even though three-fourth of the earth is covered by water. The reasons for scarcity of water are worldwide rapid growth of industry and immeasurable population. Solar still is the only efficient solution for water problem in hot climatic conditional areas where scarcity of water and electricity occurs. Solar still is a very simple solar device that is used for converting the available brackish water into potable water. Investigation shows that the productivity of basin type solar still is limited. Various literature reported several experimental and numerical investigations on basin type of solar still. An extensive review on different parameters affecting the rate of evaporation and condensation on passive solar still has been carried out in this paper.

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## 1. Introduction

Water is essential for all life forms on earth – human, plants and animals. Water is one of the most abundant resources on earth,

covering three-fourths of the planet's surface. About 97% of the earth's water is present as saltwater in oceans and the remaining 3% as fresh water in the form of ice, ground water, lakes, and rivers. Less than 1% fresh water is within human reach. Nature itself provides most of the required fresh water, through hydrological cycle.

The enormous population and rapid growth of industry lead a worldwide imbalance between supply and demand of fresh water. Most desalination plants such as reverse osmosis, membrane

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## Nomenclature

$Q$	heat transfer energy (W)
$h$	heat transfer coefficient (W/m <sup>2</sup> K)
$A$	area (m <sup>2</sup> )
$p$	partial pressure of water vapor (N/m <sup>2</sup> )
$M$	molecular weight (g/mol)
$c$	specific heat capacity (J/kg K)
$T$	temperature (°C)
$v$	mean wind velocity (mph)

## Subscripts

$b$	basin
$g$	glass

$w$	water
$c$	convection
$e$	evaporation
$a$	air
$T$	total
$p_a$	saturated vapor pressure at room temperature
$fg$	change during evaporation
$g.c$	glass cover

distillation, multistage and multiple effect distillation use fossil fuel as a source of energy. The above-mentioned treatment processes are available to supply clean potable water to rural and urban peoples. However, for the people living in remote areas, no device is available at inexpensive cost to supply drinking water. Solar distillation is a most attractive and simple technique among other treatment processes.

In 1872, Swedish engineer C. Wilson designed the first conventional solar still for supplying fresh water to nitrate mining community in Northern Chile. The operation of solar still is similar to natural hydrological cycle that includes two processes, namely evaporation and condensation. A black painted basin contains brackish water or waste water and a transparent cover is enclosed in a completely air tight area. Transparent cover passes incident solar irradiance and it is absorbed by the basin plate. Consequently basin water gets heated up and evaporates in the saturated conditions inside the still killing all pathogenic bacteria. Water vapors rises towards the cooler inner surface of the cover, where they condense to pure water. Due to gravity condensed water run down along the cover bottom surface, getting collected in a collecting tray. The still is easy to fabricate and do not require maintenance and skilled labors.

There are two types of solar stills namely active solar still and passive solar still. In active solar still additional collectors or condensers are used to enhance the productivity. In passive solar still simple modifications within basin are used to enhance the productivity.

The progress in improving the effectiveness of the single basin passive solar still has been reviewed by Kalidasa Murugavel et al. [1]. Velmurugan et al. [2] reviewed the performance analysis of solar stills based on various factors affecting the productivity. Kabeel et al. [3] reviewed the research and developments on solar still. Kaushal et al. [4] reviewed the different types of solar still. Sampathkumar et al. [5] reviewed the active solar distillation in detailed. Xiao et al. [6] reviewed the solar stills for brine desalination. However, the still productivity mainly depends on evaporation and condensation rate. Hence, the main objective of this review is on different parameters affecting the rate of evaporation and condensation on passive solar still.

## 2. Factors affecting the yield of solar still

The performance of solar still is generally expressed as the quantity of water produced by basin area in a day. The quantity of water produced by solar still varies with solar radiation available, atmosphere humidity, ambient temperature, sky conditions and wind speed, and cannot be controlled by humans as they are

meteorological parameters. The design parameters such as orientation of the still, area of absorber plate, inclination of glass cover, slopes of the cover, insulation materials, depth of water, inlet temperature of water and the temperature difference between the glass cover and the basin water affect the production rate.

## 3. Evaporation rate

The evaporative heat transfer from the basin water to the glass cover is given by Malik et al. [7]

$$Q_{e,b,w-g,c} = h_{e,b,w-g,c} A_b (p_{b,w} - p_{g,c}) \quad (1)$$

where the evaporative heat transfer coefficient from the basin water to the glass cover is given by Malik et al. [7]

$$h_{e,b,w-g,c} = \frac{M_w h_{fg} p_T}{M_a c_{pa} (p_T - p_{b,w})(p_T - p_{g,c})} h_{c,b,w-g,c} \quad (2)$$

The convective heat transfer from basin water to glass cover is given by Dunkle [8]

$$h_{c,b,w-g,c} = 0.884 \left[ (T_{b,w} - T_{g,c}) + \frac{(p_{b,w} - p_{g,c})(T_{b,w} + 273.15)}{268,900 - p_{b,w}} \right]^{2/3} \quad (3)$$

From Eq. (1) it is clear that evaporative heat transfer from basin water to the glass cover depends on the absorber plate (basin) area ( $A_b$ ) and the difference between partial pressure of basin water temperature ( $p_{b,w}$ ) and partial pressures of glass cover temperature ( $p_{g,c}$ ). Evaporation rate of still depends on basin water, glass cover and atmospheric temperature difference.

Evaporation rate of basin water is increased by adding dyes to water. Absorber area is increased by placing some kind of wick materials and absorber materials on the basin. Water temperature is increased by hot water flowing in the basin and surface heating techniques.

Evaporation rate of solar still plays an important role in productivity. Evaporation rate mainly depends on the solar radiation availability. The following factors affect the evaporation rate of solar still:

- basin construction materials;
- depth of water;
- absorption rate of basin water;
- absorption rate of still basin;
- volumetric heat capacity of the basin;
- inlet temperature of water; and
- temperature of top surface water.

### 3.1. Basin construction materials

Solar radiation that passes through the transparent cover is absorbed by saline water and the basin liner of a solar still. So, the basin liner acts as an absorber of solar radiation and it is important for the liner to have a relatively high absorptance for solar radiation [9]. In practical applications, basin liners can be made of plastic or metal-sheet [10]. Some plastics are relatively cheap while others are expensive [11]. Common metal sheets applied in solar collection are copper, aluminum and steel [12]. The important property of a metal for application in solar engineering is thermal conductivity. Copper and aluminum have relatively high thermal conductivities ( $k=200 \text{ W m}^{-1} \text{ K}^{-1}$  for aluminum and  $k=390 \text{ W m}^{-1} \text{ K}^{-1}$  for copper) while the thermal conductivity of steel is relatively low ( $k=48 \text{ W m}^{-1} \text{ K}^{-1}$ ). Nevertheless, copper and aluminum are more expensive (more than two times the cost of galvanized steel).

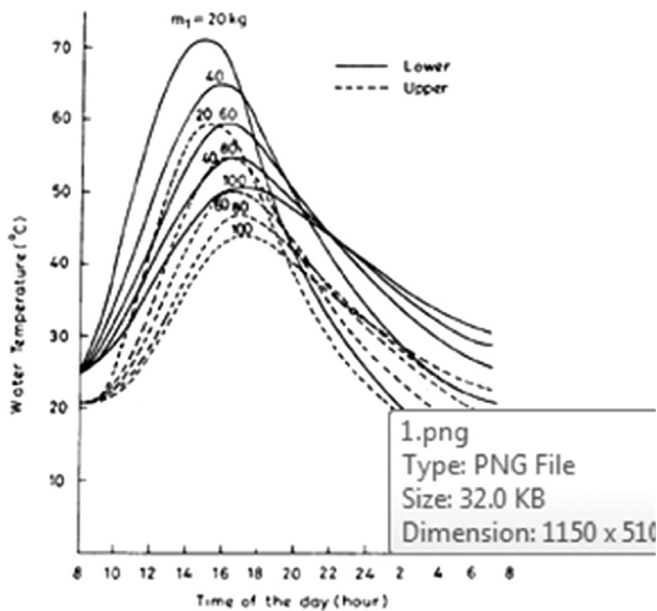


Fig. 1. Effect of water depth in the lower basin on the hourly variation of the total yield [14].

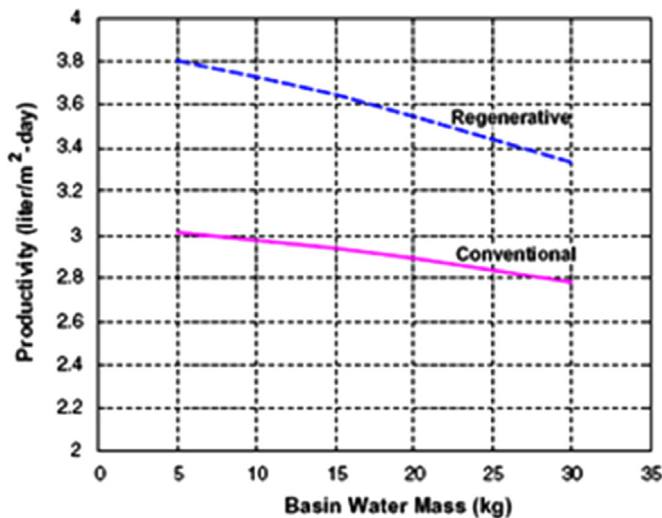


Fig. 2. Variation of stills productivity with basin water mass [15].

### 3.2. Depth of water

The evaporation rate of solar still is inversely proportional to the depth of water. The minimum depth of water has higher heat transfer coefficient and hence it gives higher productivity [1].

Ahsan et al. [13] developed a low cost solar still used in rural and coastal areas for converting saline water into potable water. They evaluated water productivity by varying the water depths

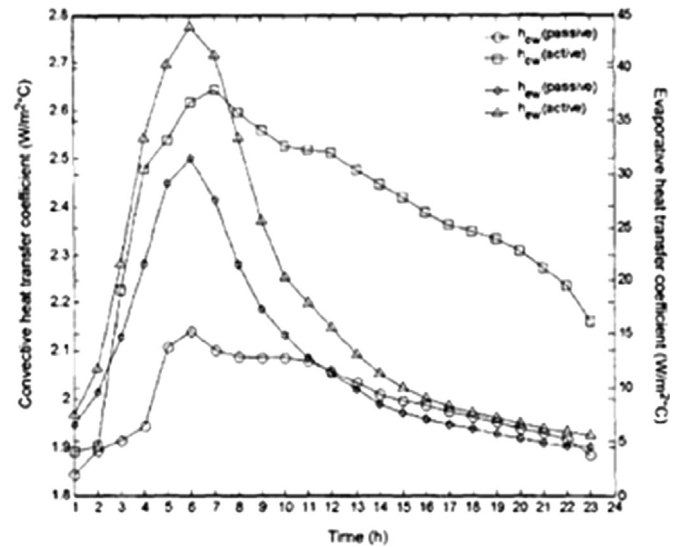


Fig. 3. Hourly variation of convective and evaporative heat transfer coefficient in passive and active mode for 0.15 m [16].

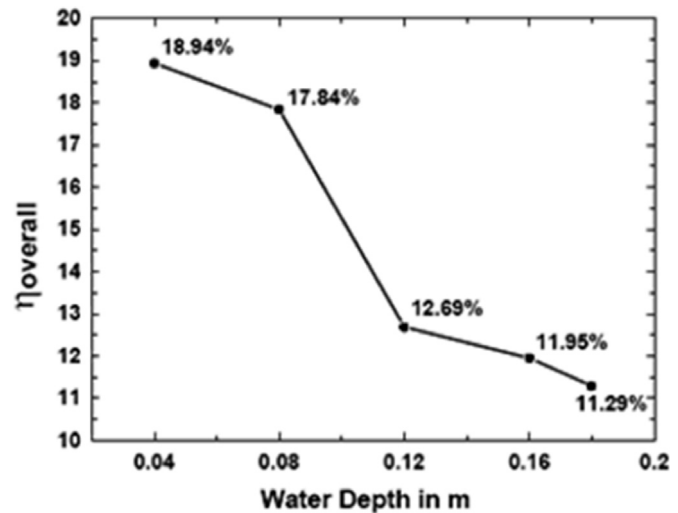


Fig. 4. Variation of overall efficiency with respect to all water depths [17].

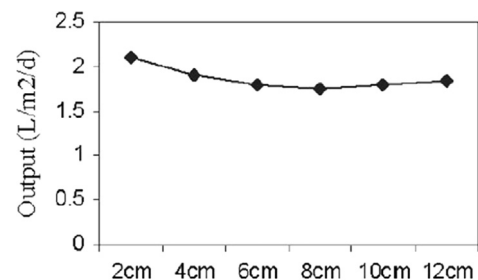


Fig. 5. Variation of distillate with water [18].

(1.5, 2.5 and 5 cm) and concluded that the water productivity is inversely proportional to the water depth.

Suneja et al. [14] investigated the effect of water depth on the performance of an inverted absorber double basin solar still. It was found that the output of an inverted double basin solar still increases with the decrease of water depth in the lower basin for a given water mass in the upper basin. From Fig. 1 it is evident that water at minimum depth ( $m=20$  kg) gives higher yield at day time and after that it gets reduced.

Zurigat et al. [15] found that, the increase in water mass decrease the productivity of the solar still (Fig. 2).

Tripathi et al. [16] investigated the effect of water depth on internal heat and mass transfer for active and passive solar distillation. The temperature difference between the glass and basin water was achieved by feeding hot water into the basin from the collector through a pump. During the sunshine hours, i.e., from 9 am to 4 pm the pump was operated, and was kept off during off-sunshine hours to avoid heat losses caused by reverse flow. They investigated the water depth in the basin (0.05, 0.1, and 0.15 m) for passive and active solar still. The output was higher when the water depth in solar still was 0.1 m and 0.15 m (Fig. 3) during the off shine hours.

Tiwari et al. [17] found the effect of water depths on heat and mass transfer in a solar still in summer climatic condition. They found that for minimum water depth, higher productivity is achieved due to increase in convective and evaporative heat transfer coefficient. Fig. 4 shows that water at depth of 0.04 m has given higher efficiency than water at a depth of 0.08, 0.12, 0.16 and 0.2 m.

Phadatare et al. [18] investigated the influence of water depth on internal heat and mass transfer in a plastic solar still. They conducted tests with different depths of water level such as 0.02, 0.04, 0.06, 0.08, 0.1, 0.12 m. At 2 cm depth of water level the still productivity achieved was as high as 2.1 L/m<sup>2</sup>/day (Fig. 5). The efficiency of the plastic solar still varied from 10% to 34%. The results show that the solar still productivity decreases, when there was an increase in depth of basin water.

Kalidasa Murugavel et al. [19–21] conducted experiments related to mass of water in single basin double slope solar still and they found that minimum mass of water gives higher productivity.

Dev et al. [22] performed comparative study of inverted absorber solar still and single slope solar still with water depth and dissolved salts. The daily productivity obtained at water depth of 0.01 m has given better productivity for both inverted absorber solar still and single slope solar still. The productivity rate of water

was 6.302 kg/m<sup>2</sup>/day and 2.152 kg/m<sup>2</sup>/day for inverted absorber solar still and single slope solar still respectively.

### 3.3. Absorption rate of basin water

Still basin reflects back around 11% of solar radiation without using it [7]. This loss can be reduced by increasing the absorption coefficient of basin water. The absorption coefficient of basin water can be improved by adding dye to the basin water [15,22,24–26].

Kabeel et al. [23] enhance the solar still productivity by modified solar still and using nanofluids. They used aluminum-oxide nanosized solid particles in water; it changed the heat transfer characteristics and evaporative properties of the water. Their results showed that the usage of nanofluids improve the solar still productivity by about 116% when the still integrated with the external condenser.

Effect of adding dyes to a solar still was analytically and experimentally studied by Rajvanshi [24]. The transient heat transfer inside the dye solution was analytically developed as one dimensional mode (Fig. 24). The dyes used are black naphthylamine, red carmoisine and dark green. Among the dyes tested black naphthylamine dye was found most suitable because of the two reasons i.e. no photochemical degradation and increased evaporation. When the dye is added with water, the solar radiation is absorbed by the upper layer and the temperature of upper layer water increases, which in turn increases the evaporation rate. The result show that a dye solution is able to increase the distillate output by as much as 29% (black dye with 172.5 ppm concentration). The amount of solar energy absorbed by dye's are in the order of black dye > green dye > red dye > water (Fig. 6).

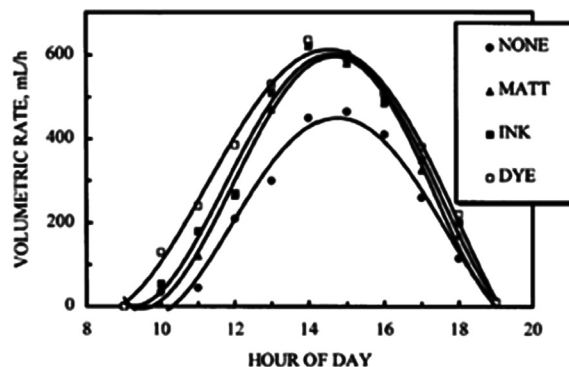


Fig. 7. Water collected as a function of the hour of the day [25].

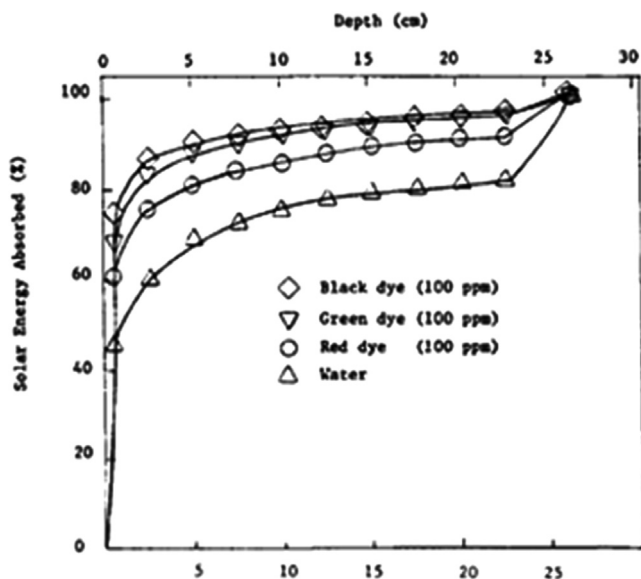


Fig. 6. Percentage of solar energy absorbed with depth of solution [24].

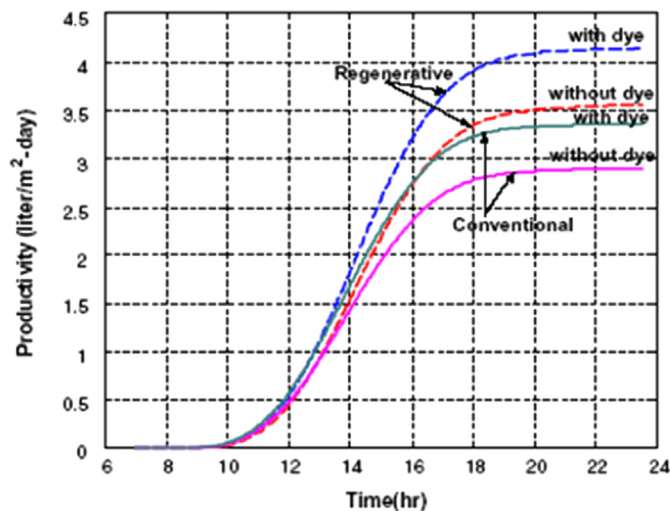


Fig. 8. Productivity of stills with and without dye [15].

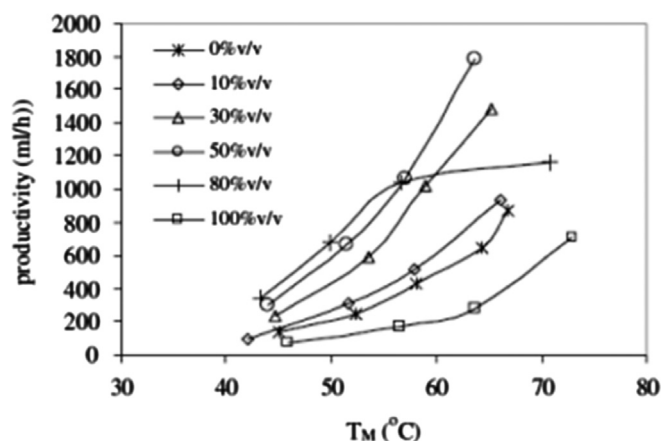


Fig. 9. Measured productivity as a function of solution temperature and concentration [28].

Akash et al. [25] studied the effect of addition of absorbing materials in a single basin solar still with double slopes. They found that using black rubber mat increases the daily water productivity by 38%, black ink by 45% and black dye by 60% (Fig. 7). Black dye can absorb solar radiation at higher rates compared to other materials.

Zurigat et al. [15] compared the effect of dye on the productivity of regenerative and conventional solar stills. It was found that at the use of dye results in about 17% and 16% increase in productivity for regenerative and conventional solar stills respectively. Dye is normally added to increase the absorptance of water and hence more solar energy is absorbed directly by the water (Fig. 8). The dye may be made of coal dust or any miscible black color agent.

Nijmeh et al. [26] studied the effect of using various absorbing materials on the productivity of a single-basin solar still. The materials used to enhance the absorptivity of water for solar radiation include dissolved salts, violet dye, and charcoal. The salts were potassium permanganate and potassium dichromate. They found that the addition of potassium permanganate resulted in 26% increase of efficiency. The best result was obtained by using violet dye with an increase of about 29% efficiency.

Suresh et al. [27] used oxides like  $\text{CuO}$ ,  $\text{PbO}_2$ ,  $\text{MnO}_2$ , metal sulfides like  $\text{PbS}$ ,  $\text{CuS}$ ,  $\text{Bi}_2\text{S}_3$  and  $\text{Sb}_2\text{S}_3$  and dyes like Malachite Green, Fuschine and Alizarin Reds as photo catalysts to improve the rate of production. Among the materials that are used as photo catalysts it was found that oxides are better than sulfides and dyes.

Ayuthaya et al. [28] investigated the thermal performance of an ethanol solar still with fin plate to increase productivity. It was found that the productivity of the modified solar still was increased by 15.5% when 10% v/v alcohol solution was mixed with water. Fig. 9 shows that productivity increases with solution temperature. The boiling condition might enhance the productivity because molecules anywhere in liquid could escape to a gas phase.

### 3.4. Absorption rate of still basin

The absorption rate of still basin is increased by different types of absorbing material along with basin water. Absorption rate of basin can be improved by using absorbing materials like charcoal, matt, sponge, jute cloth, and cotton cloth.

Kannan et al. [29] designed, fabricated and investigated the vapor adsorption basin solar still. They integrated the basin with vapor adsorption pipe network comprising activated carbon–methanol pair. It reduced losses from the bottom of the still.

Pankaj et al. [30] used low thermal inertia porous absorbers were made up of ordinary blackened jute cloth in single sloped basin type solar still. Low thermal inertia of the porous absorber

increased higher operating temperature and higher productivity. Also the increase in the evaporation surface area further aided the performance. They got about 68% more distillate output on clear days, whereas it was nearly 35% more on cloudy days.

Tiris et al. [31] improved the performance of solar still by using absorbing materials. Three types of absorbing materials were tested under natural solar radiation. They were charcoal, blackened rock-bed, and black-paint. Results from Fig. 10 show that charcoal gave the best efficiency (11–18% more than black-paint, 23–92% more than blackened rock-bed). During the summer months water level in the still also plays an important role in the productivity.

Naim et al. [32] designed a solar still with charcoal as heat absorbing medium and wick material. They used three different charcoal sizes such as coarse, intermediate and fined. At higher flow rates both coarse and intermediate sizes gave better productivity. At moderate and low flow rates fine charcoal gave slightly better productivity. The reason for this may be attributed to the fact that coarser the charcoal is, glossier is its surface resulting in light reflection through the cover with consequent heat loss. It was found that charcoal can be used as absorbing medium successfully instead of wick type, black butyl rubber, and asphaltic absorber. A 15% improvement in productivity over wick type stills (Fig. 11) has been attained.

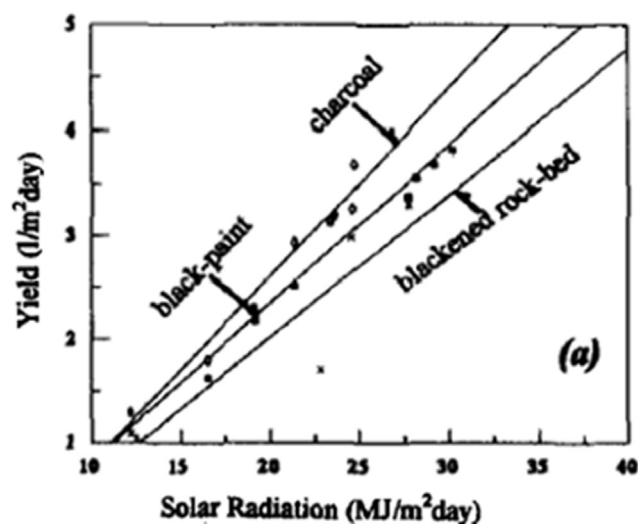


Fig. 10. Correlations between daily yield and solar radiation for different absorber materials [31].

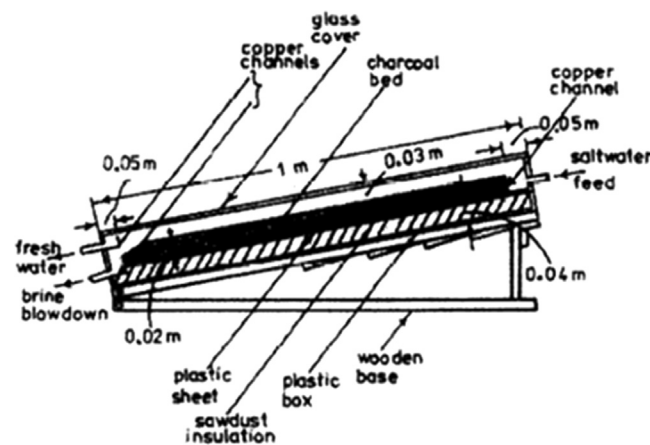


Fig. 11. Schematic diagram of the charcoal solar still [32].

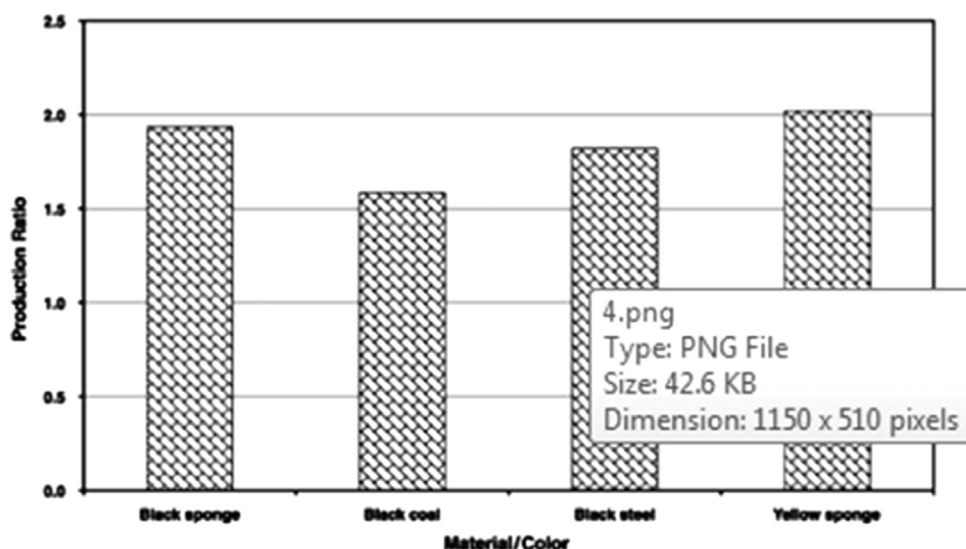


Fig. 12. Change in production ratio with material and color of cubes used [33].

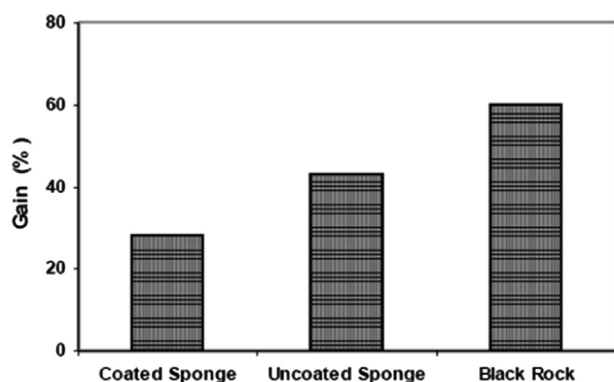


Fig. 13. Percentage gain in distilled water yield for various absorbing materials [34].

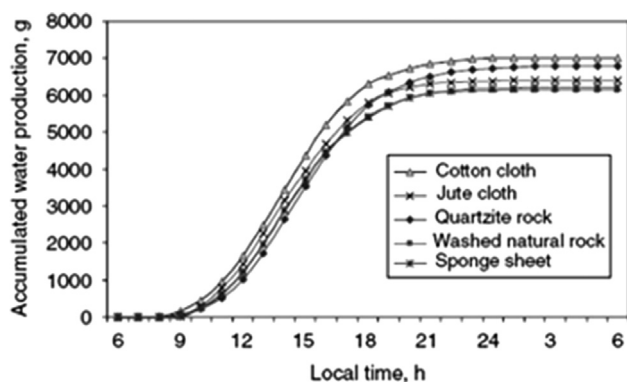


Fig. 14. Variation of accumulated water production of the still [20].

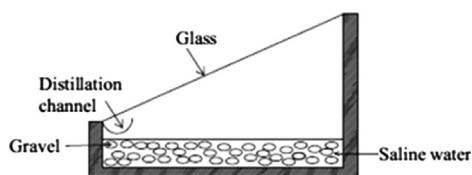


Fig. 15. Solar still with gravel [36].

Bassam et al. [33] investigated the solar still with different sizes of sponge cubes. They used black sponge, yellow sponge, black coal, and black steel. Among the materials used they found that

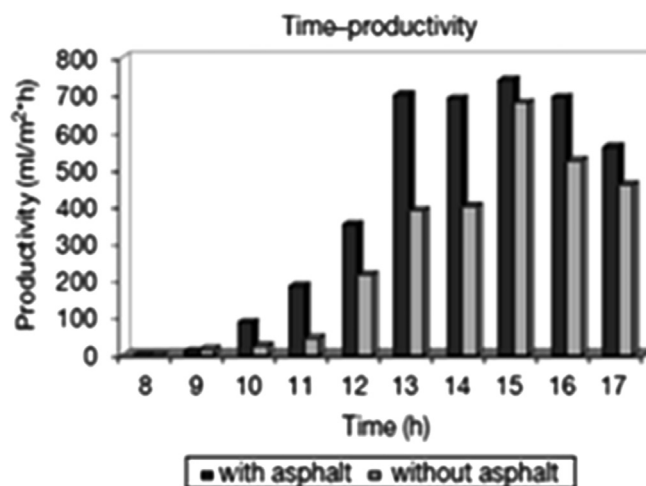


Fig. 16. Relation between the time and productivity due to asphalt basin liner effect [38].

yellow sponge cubes gives more productivity compared to black coal and steel (Fig. 12). The output of the still was increased from 18% to 27.3%.

Abdallaha et al. [34] used coated, uncoated and black volcanic rocks as absorbing materials in single slope solar still (Fig. 13). They manufactured four different types of solar still. The first three solar stills contained black coated metallic wiry sponges, uncoated metallic wiry sponges, and black rocks collected from Mafraq area in north-eastern Jordan. The fourth still was used as reference solar still which contains no absorbing material. The results show that the uncoated metallic wiry sponge has the highest water productivity during the day time compared to other stills. Black rocks have the highest water productivity at the night time because of the storage effect. Black rocks store the heat and it releases heat at the time of night. The overall efficiency of still was 28% for black coated metallic wiry sponges, 43% for uncoated metallic wiry sponges and 60% for black rocks.

Kalidasa Murugavel et al. [20] studied the performance of basin type double slope solar still with different wick materials and minimum depth of water in the basin. They used light jute cloth, 2.5 cm thick coir mate pieces, waste cotton pieces, light black cotton cloth and 3 mm sponge sheet. Among the materials used

they found that light black cotton cloth gives higher productivity compare to other materials (Fig. 14).

Kalidasa Murugavel et al. [19] experimentally studied the performance of solar still with thin layer of water in the basin. They used wick materials and porous materials to maintain the thin layer of water basin. They used wick materials like light cotton cloth, light jute cloth, and 2 mm thickness of sponge sheet and porous materials like washed natural rock and quartzite rock as spread materials. Higher productivity was obtained when black light cotton cloth was used as spread material.

### 3.5. Volumetric heat capacity of the basin

Sun provides an abundant supply of energy but it is intermittent and unpredictable. Some kind of storage materials are used in solar still to store the energy when it is available and to release it during the night time. Glass, rubber, gravel, are some materials having these properties [1].

Ansari et al. [35] developed transient mathematical models for passive solar still with a three types of PCMs which have different melting temperatures as heat energy storage medium. They found that PCMs stored the excess heat energy during sunshine times and use later during the night. They compared the brackish water temperature with the analytical expression and the existing results in the literature.

Nafey et al. [36] investigated solar still productivity by using energy storing materials like 10 mm size black rubber sheet and 20–30 mm size black gravel. By using 10 mm size black rubber sheet the improvement in solar still productivity achieved was 20%. The solar still with gravel is shown in Fig. 15. By using 20–30 mm size black gravel the improvement in solar still productivity achieved was 19%. Velmurugan et al. [37] achieved 20% in productivity of still by adding pebbles.

Badran [38] studied the effect of using asphalt in the basin as an energy storing material. The use of asphalt in the basin resulted in significant improvement of still production up to 29%. When the sprinkler was combined with asphalt the production rate increased up to 51%. Also the productivity during night contributed to around 16% of the total day around productivity (Fig. 16).

El Sebaei et al. [39] investigated the single slope–single basin solar still with baffle suspended absorber. It was found that the productivity of solar still with baffle suspended absorber improved 20% higher than the conventional solar still (Fig. 17).

Sakthivel et al. [40] studied black granite gravel (Fig. 18) as energy storage medium in a solar still. They found that the still productivity increased up to 17–20% compared to conventional solar still.

Kalidasa Murugavel et al. [21] investigated the single basin double slope solar still with minimum depth of water and energy storing materials. They used energy storing materials like 1/4" quartzite rock, 1/4" naturally washed stones, 3/4" quartzite rock, 1 1/2" cement concrete pieces, 11/4" red brick pieces, mild steel scraps. Among the energy storing materials used they found that 3/4" sized quartzite rock is the effective basin storage material (Fig. 19).

Fath [41] reported that phase change material (PCM) stores large amount of energy per unit volume and constant temperature for charging and discharging of the material.

Radhwan [42] analyzed the stepped solar still with consisting the latent heat thermal energy storage system. He used phase change material as storage medium. He has found that the productivity of the solar still to be 4.6 L/m<sup>2</sup>/day with 57% efficiency for paraffin wax.

Sabaii et al. [43] investigated the performance of a single basin solar still with PCM as a storage medium. They found that the day time productivity decreases with increase in mass of PCM, whereas the productivity during over nights and daily increases appreciably with increase in mass of PCM (Fig. 20). At the time of discharging of PCM, heat transfer coefficient from the basin to water gets doubled. They got a productivity of 9.005 L/m<sup>2</sup>/day with a daily efficiency of 85.3% compared to conventional solar still with a productivity of 4.998 L/m<sup>2</sup>/day. Thus PCM is more effective than sensible heat storage materials.

### 3.6. Inlet temperature of water

Sodha et al. [44] utilized the waste hot water from thermal power plant for distillation. Their results showed that, still which has been filled with hot water once in a day does not give higher

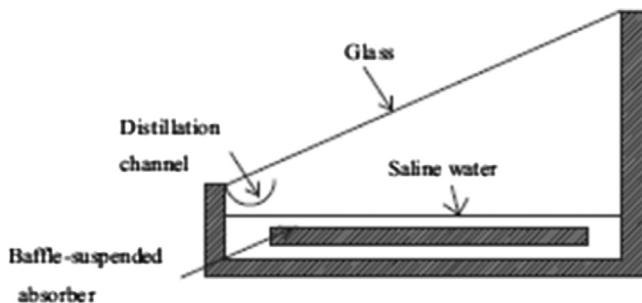


Fig. 17. Solar still with baffle suspended absorber [39].

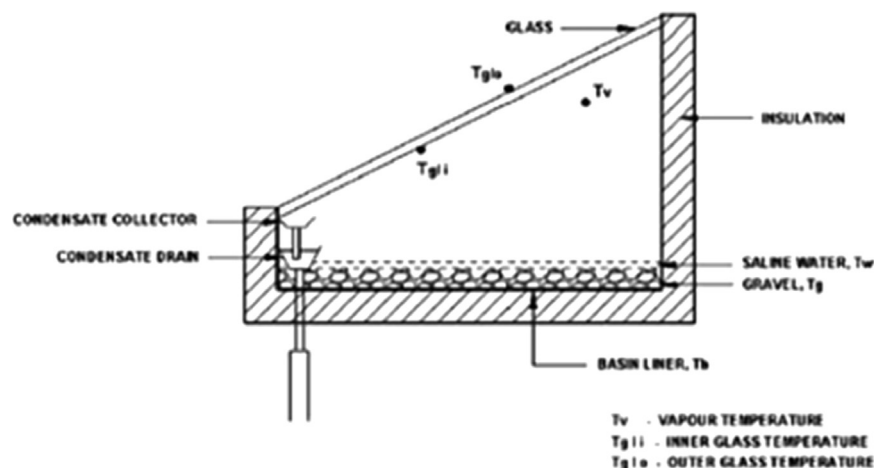


Fig. 18. Sectional view of the solar still with gravel [40].

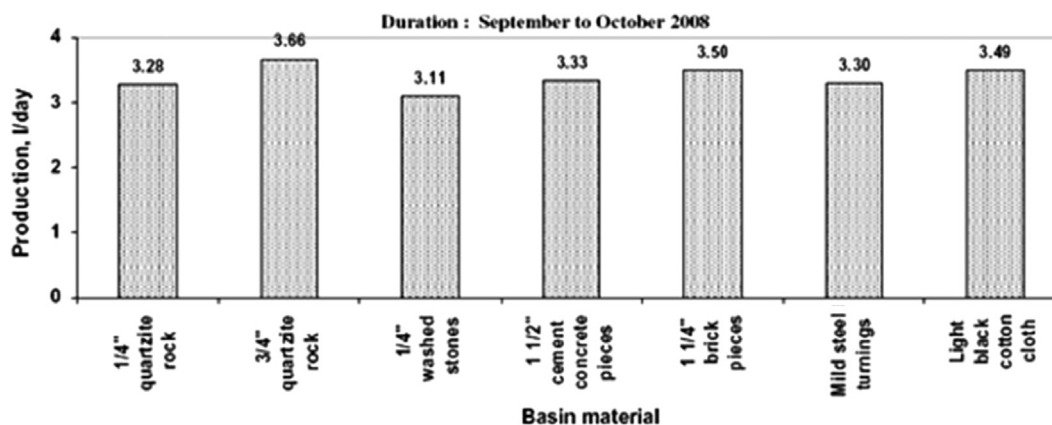


Fig. 19. Overall productions – different material [21].

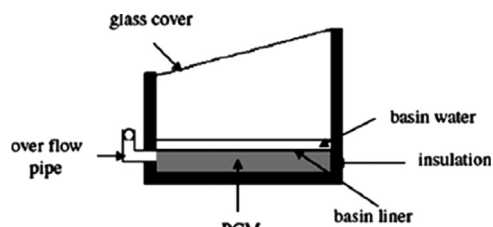


Fig. 20. Schematic diagram of the single slope–single basin solar still [43].

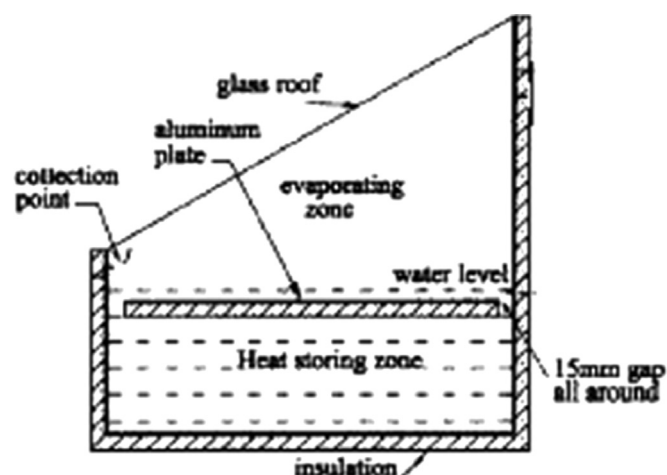


Fig. 23. Solar still with aluminum black painted plate [48].

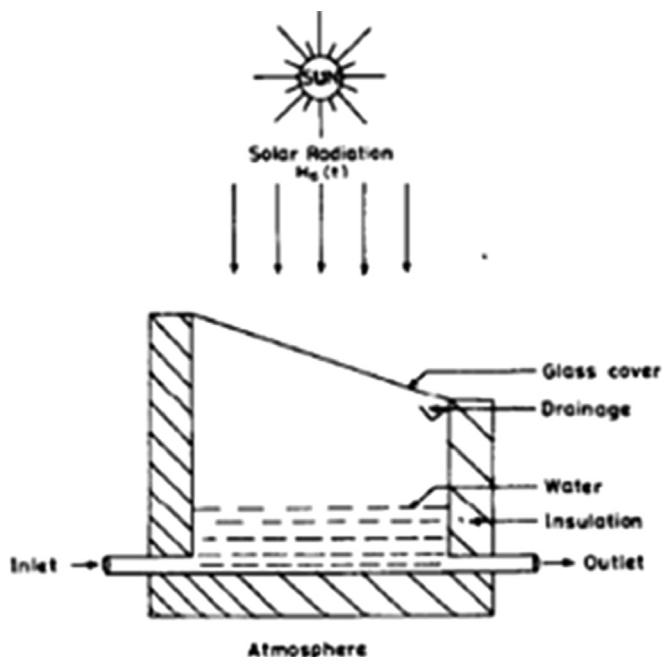


Fig. 21. Schematic sketch of single basin solar still [45].



Fig. 24. The modified still with the folded, perforated and black coated sheet floating over the water surface (shown with the glass cover removed) [49].

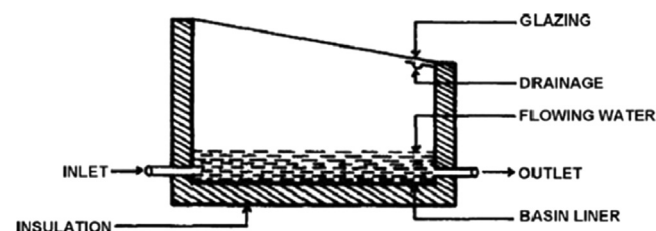


Fig. 22. Schematic of a single basin solar still with water flow in the basin [47].

productivity when compared to the still fed with constant hot water. Madhuri et al. [45] investigated the solar still with intermittent flow of waste hot water in the basin (Fig. 21). Waste hot water is fed into the basin during off sunshine hours which results in higher temperature of water and higher productivity.

Tiwari et al. [46] investigated a single basin solar still with flow of waste hot water in the basin. The productivity of solar still was increased by increasing the inlet temperature of basin water during off-sunshine hours. The productivity of solar still was

better when the hot water flows to the basin continuously. The productivity of still by continuous flow of hot water shows a subsidiary improvement over that of Madhuri et al. [45].

Yadav et al. [47] investigated a single basin solar still with water flow in the basin (Fig. 22). They found that, decreasing mass flow rate increases the water temperature, distillate output and efficiency of the system. 0.00027 kg/m<sup>2</sup> s is the optimum value of the mass flow rate through the basin of the still.

### 3.7. Temperature of top surface water

The evaporation rate of solar still mainly depends on the temperature of top surface water. To heat the total mass of water in the basin, high energy is required. For getting high temperature at top surface less amount of heat is required [1]. Deep basin still with a technique of surface heating by an aluminum plate is shown in Fig. 23. Aluminum plate receives the solar radiation and it was used to heat the top layer of water to enhance the productivity. At 2 cm of water layer, aluminum plate with black painted increases the efficiency by 28% [48].

Valsaraj et al. [49] designed a solar still with black coated sheet floating, folded and perforated over the water surface as shown in Fig. 24. They found that black coated sheet floating absorber sheet design was having higher output compared to others. The productivity of the still was increased by 43%.

El Sebail et al. [50] modified single basin solar still with mica plate as a suspended absorber. The daily productivity of the still was 42% higher than the conventional solar still. Nafey et al. [51] enhanced the solar still productivity by using perforated aluminum black plate (Fig. 25) as a surface heating technique. At 3 cm

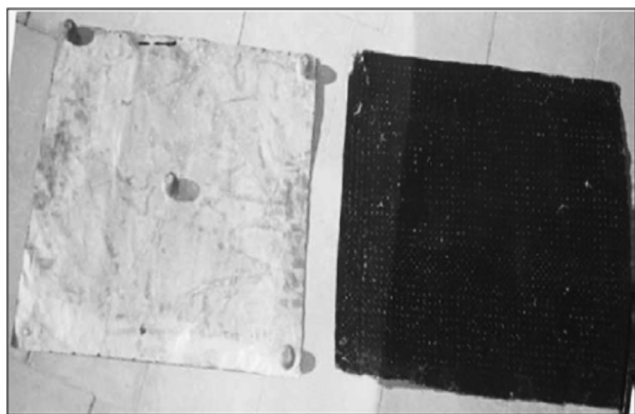


Fig. 25. Photograph of perforated aluminum black plate [51].

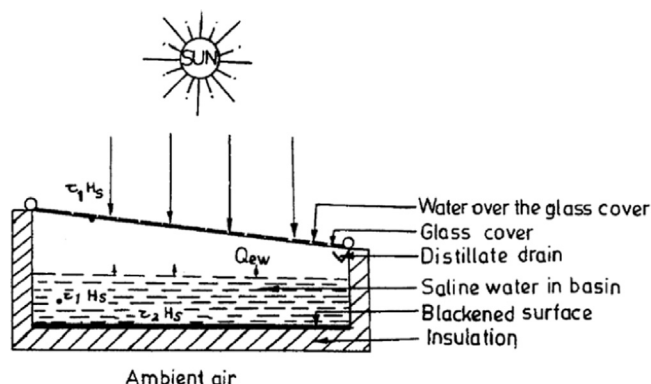


Fig. 26. Schematic representation of the single basin solar still with water flowing over the glass [56].

brine depth, the efficiency of the still was 15% and at 6 cm brine depth the efficiency of the still was 40%.

Kalidasa Murugavel et al. [20], Ayuthaya et al. [28] and Velmurugan et al. [52,53] used fin basin plate to increase the productivity of still by effective absorbance of solar radiation.

Kalidasa Murugavel et al. [21] enhanced the solar still productivity by using aluminum fin of size 65 mm × 45 mm covered with light black cotton and jute cloths. They arranged an aluminum rectangular fin which has been covered with jute and cotton cloths as breadth wise and length wise direction in the basin. They found that aluminum rectangular fin and cotton cloth with lengthwise direction gives more productivity when compared to other combinations.

Ayuthaya et al. [26] investigated the thermal performance of an ethanol solar still with fin plate. They found that basin solar still with a set of fin-plate fitting in the basin increased the productivity by 15.5%.

Velmurugan et al. [52] designed a single basin solar still with fin for enhancing productivity. They found that there was an increase of 45.5% in the productivity of saline water distillation. Velmurugan et al. [53] designed an effluent desalination plant using fin type basin plate. They found that there was an increase of 53% in the productivity of industrial effluent distillation.

## 4. Condensation rate

The convective heat transfer from the glass cover to the atmosphere is given by Kalogirou Soteris [54]

$$Q_{c,g,c-a} = h_{c,g,c-a} A_{g,c} (T_{g,c} - T_a) \quad (4)$$

The convective heat transfer coefficient from the glass cover to the atmosphere is given by Watmuff et al. [55]

$$h_{c,g,c-a} = 5.7 + 3.8 V \quad (5)$$

From Eq. (4) it is clear that the convective heat transfer from the glass cover to atmosphere depends on the area of glass cover ( $A_{g,c}$ ) and temperature difference between the glass cover ( $T_{g,c}$ ) and the atmosphere ( $T_a$ ). The convective heat transfer coefficient mainly depends on the wind velocity. Temperature difference between water and glass is achieved by either increase the temperature of water or decrease the temperature of glass cover. Glass temperature is reduced by flowing cold water over the glass cover and flowing the water between double glass cover.

The output of solar still is high when the condensed water on the bottom surface of the glass cover is high. The rate of condensation is higher, when the condensing heat transfer from the glass to atmosphere by convection and evaporative heat

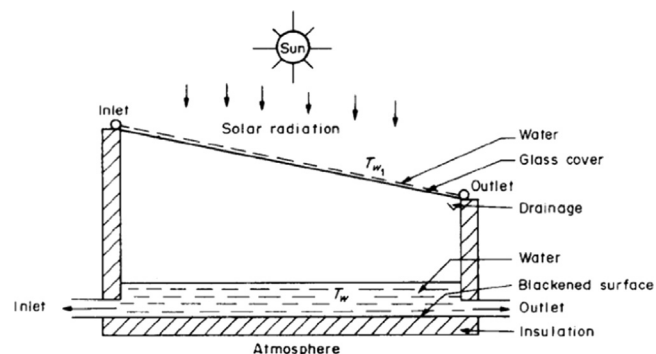


Fig. 27. Schematic representation of single basin solar still with water flowing over the glass cover and inside the basin [46].

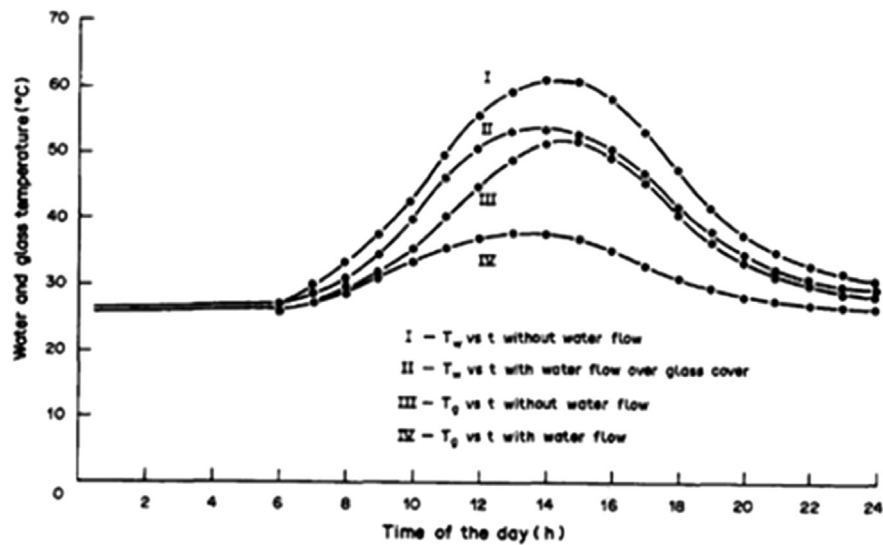


Fig. 28. Hourly variation of water and glass temperature variation with and without water flow [57].

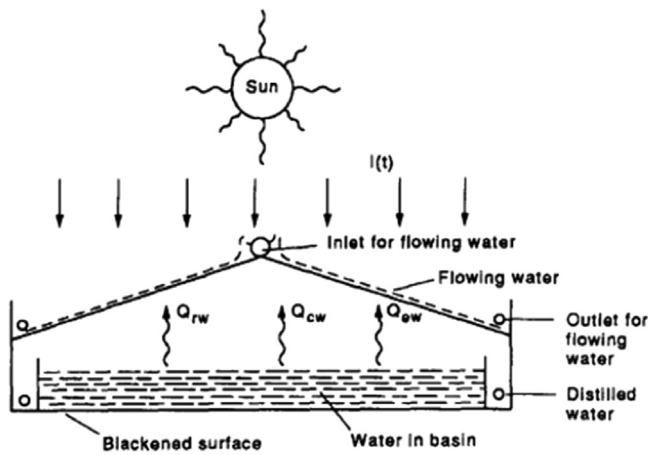


Fig. 29. Flowing water over the glass [58].

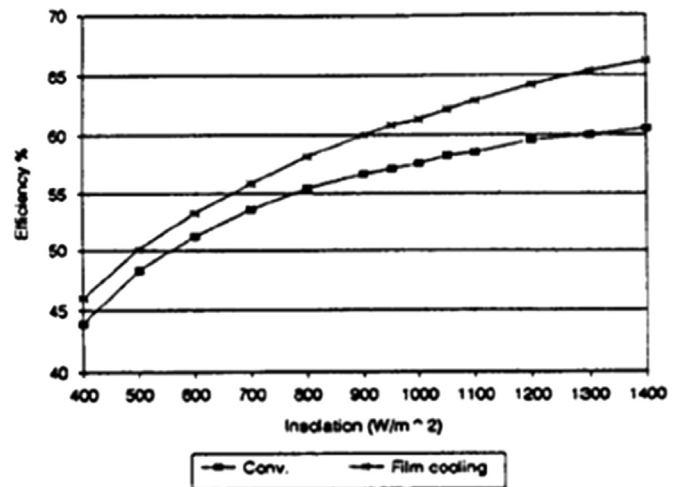


Fig. 30. Steady state efficiency vs. incident insolation [60].

transfer from the basin water to glass cover by radiation are high. To increase the production rate of solar still, the condensation rate should be increased. Condensation rate can be increased by reducing the inner glass temperature of the cover. The natural circulation of air mass inside the still is increased by maintaining the temperature difference between the glass cover and the basin water [1]. The following factors affect the condensation rate:

- glass cover temperature and
- wind speed.

#### 4.1. Glass cover temperature

The productivity of still mainly depends on the temperature difference between basin water and condensing glass cover, and increases with high temperature difference. Tiwari et al. [56] studied the performance of single basin solar still with flow of water over the glass cover (Fig. 26) and the following conclusions have been made:

- by introducing a uniform flow of water over the glass cover, the daily productivity of the still is almost doubled and

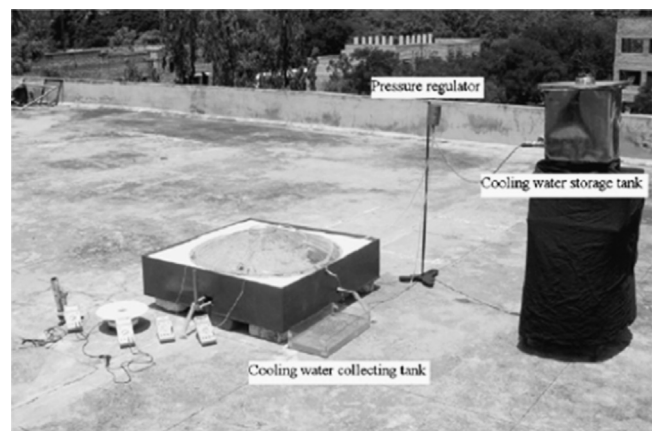


Fig. 31. Solar still showing cooling water system [61].

- the distillate output slightly decreases with the increase of water flow over the glass due to reduction in basin water temperature.

Tiwari et al. [46] reduced the glass cover temperature by an intermittent flow of cooling water on the cover of single basin solar still. The glass cover temperature was slightly higher than the ambient temperature and the flowing water temperature over the glass cover remains of the same order as ambient temperature (Fig. 27).

Lawrence et al. [57] investigated the effect of heat capacity on the performance of solar still with water flow over the glass cover. From Fig. 28, it is clear that, flow of water over the glass cover reduces the water temperature as well as glass temperature. Reduction in basin water temperature slightly reduces the evaporation rate. Reduction in glass temperature increases the condensation rate, due to which productivity of the still improved.

Singh et al. [58] found the analytical expression for thermal efficiency of a passive solar still by using energy balance equations for the different components of a passive solar still (glass cover, basin liner and water mass) with water flowing over the glass at uniform velocity. On basis of the analytical results obtained, it was found that there is a significant increase in the efficiency of the solar still due to water flow over the glass cover at higher depths of water in the basin (Fig. 29).

Kumar et al. [59] studied the transient model and comparative study of concentrator coupled regenerative solar still in forced circulation mode. The theoretical performance of the concentrator coupled regenerative and non-regenerative solar still is compared with a collector coupled still by using energy balance equation of the different component of the concentrator and non-regenerator solar still. They found that the yield of the concentrator assisted regenerative solar still is much higher than any other active/passive regenerative or non-regenerative solar still. The overall efficiency increases with an increase in the flow rate of the flowing cold water over the glass cover.

The glass cover temperature was reduced by a film of cooling water continuously over the glass cover by Abu-Hijleh et al. [60]. By proper use of film cooling the efficiency of solar still was increased by 6% as shown in Fig. 30, but poor combinations of film cooling lead to reductions in still efficiency. Temperature of flowing water over the glass cover and that of glass are always nearly equal. The best combination of film cooling parameter was: film thickness of  $2e^{-4}$  m, cooling water volumetric flow rate per unit width of  $5e^{-7}$  m<sup>3</sup>/s m, and glass cover length of 2 m.

Arunkumar et al. [61] designed a solar still with a hemispherical top cover with and without flowing water over the cover (Fig. 31). They found that the daily distillate output of the system increased with water flowing over the glass cover. The efficiency was 34% without top cover cooling and 42% with top cover cooling.

Second method that was used to reduce the temperature of glass cover is by passing water between double-glass cover. This technique is used to remove the heat of the glass cover by flowing of water in between them.

Abu-Arabi et al. [62] investigated the performance analysis of solar distillation unit with double glass cover cooling technology.

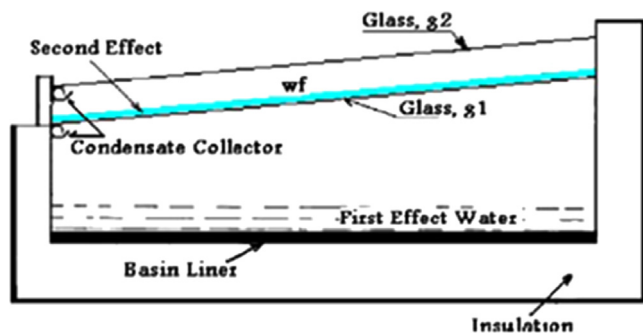


Fig. 32. Schematics of the regenerative solar still [15].

They designed a glass cover technology with no space between the upper glass cover and flowing water. The advantage of the system was that no evaporation takes place from the cooling water.

Zurigat et al. [15] designed a regenerative solar still with provision of cooling water to flow in and out of the second effect. It was just opposite to previous technique with providing the space between water and glass cover (Fig. 32). The above said technique has the advantage of cooling the lower basin glass cover by upper basin and condensed water collected at the upper basin also. The heated water from the upper basin was given to the lower basin to improve the evaporation rate and productivity. The productivity of regenerative solar still was 20% higher than conventional solar still.

#### 4.2. Wind speed

Wind velocity has a significant effect on glass temperature. At higher wind velocity, due to higher convective heat transfer from

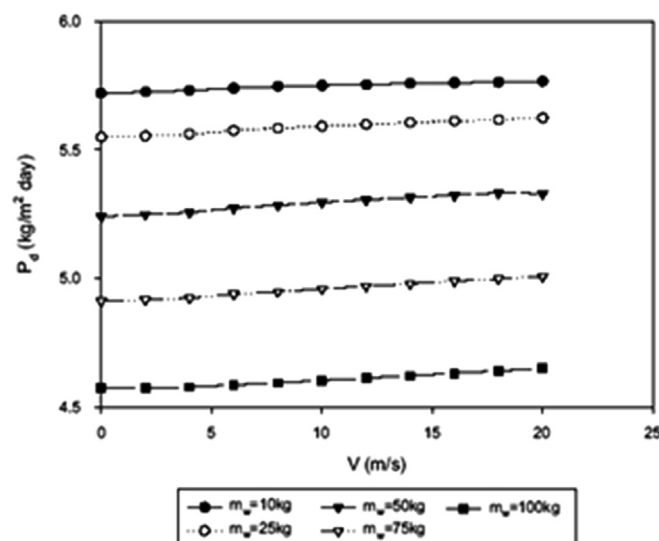


Fig. 33. Effect of wind speed  $V$  on daily productivity for different water masses [68].

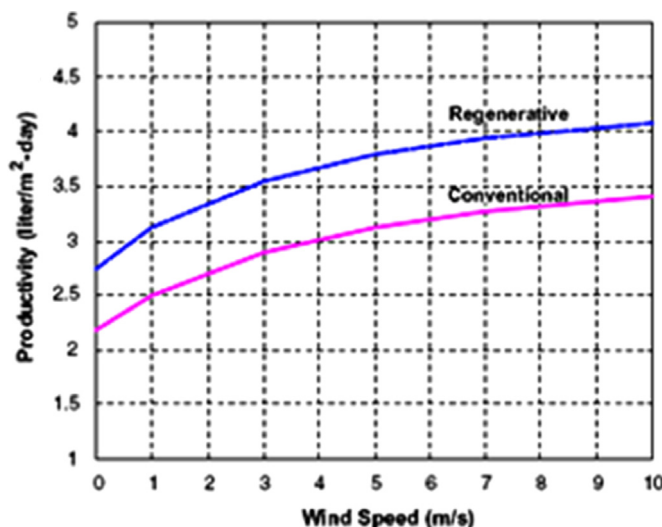


Fig. 34. Effect of wind speed on productivity of still [15].

**Table 1**

The various research works done on solar still to improve the evaporation rate.

Sl. no.	Experimental work done	Performance of the still	Remarks
1	Minimum depth in the lower basin of an inverted absorber double basin solar still [14].	Total yield of the system is maximum for low water depth in the lower basin.	The total yield of double basin solar still decreases with increase of water depth in the lower basin.
2	Effect of water depth on heat and mass transfer in a passive solar still [17].	At 0.04 m water depth the efficiency of solar still is 18.94% and at 0.2 m the efficiency of solar still is 11.29%.	Convective and evaporative heat transfer Co-efficient is significant for varying water depths to optimize the highest yield in summer climatic condition for a single-slope passive solar distillation unit.
3	Water depth on internal heat and mass transfer in a plastic solar still [18].	At 2 cm depth of water the still yield is 2.1 L/m <sup>2</sup> /day. The efficiency of the plastic solar still varies from 10% to 34%.	When plastic is used as cover plate with solar intensity of 550 W/m <sup>2</sup> , the cover temperature exceeds the basin water temperature This will affect the still productivity.
4	Water depth of inverted absorber solar still (IASS) and single slope solar still (SS) [22].	The productivity rate of water is 6.302 kg/m <sup>2</sup> /day and 2.152 kg/m <sup>2</sup> /day for IASS and SS respectively.	Optimum water depth for IASS is 0.03 m. Further addition of reflector under the basin does not affect its performance much more in comparison to that of the SS.
5	Effect of adding dyes to a solar distillation [24].	The output of the still is increased by 29%. The amount of solar energy absorbed by dye's is of the order: Black dye > green dye > red dye > water.	For the same concentration of dye, increasing the water depth will increase the productivity.
6	Effect of absorbing materials in a single basin solar still with double slopes [25].	The daily water productivity increased by 38%, 45%, 60% by using black rubber matt, black ink and black dye respectively.	Increasing the productivity of water would reduce the effective insolation area of a solar still.
7	Effect of dye on their productivity in regenerative and conventional solar still [15].	Use of dye results in about 17% and 16% increase of productivity for regenerative and conventional solar still respectively.	Dye reduces the distillate quality.
8	Effect of using various absorbing materials on the productivity of a single-basin solar still [26].	Addition of potassium permanganate resulted in 26% increase of efficiency. The best result is obtained by using violet dye with an increase of about 29%.	Dye reduces the distillate quality.
9	Effect of photo catalysis in solar still [27].	Oxides (CuO, PbO <sub>2</sub> , MnO <sub>2</sub> ) are better than metal sulfides (PbS, CuS, Bi <sub>2</sub> S <sub>3</sub> and Sb <sub>2</sub> S <sub>3</sub> ) and dyes (Malachite Green, Fuschine and Alizarin Reds).	Photo catalysts are active only in the presence of light energy.
10	Thermal performance of an ethanol solar still with fin plate to increase productivity [28].	Still productivity is increased by 15.5% by using 10% v/v alcohol solution.	By increasing the number of fins, the still efficiency can be increased up to 46%.
11	Effect of absorber materials on solar still [31].	Charcoal gives the best results (11–18% more than black-paint, 23–92% more than blackened rock-bed).	Bu integrating flat plate collector and storage systems the yield can be increased up to 194%.
12	Solar still with charcoal as heat absorber medium and wick [32].	A 15% improvement in productivity over wick type stills is archived.	It is cheaper, simple in construction, low thermal capacity and light weight compared to wick type still.
13	Solar still with sponge cubes in basin [33].	Output of still is increased from 18% to 273% compared to still without sponge cubes.	Does not require frequent maintenance after installation.
14	Thermal performance of solar still by using various absorbing materials [34].	The overall productivity of solar still is 28%, 43% and 60% for coated and uncoated metallic wiry sponges and black rocks respectively.	Due to salt concentration at basin, metallic wiry sponges are corroded easily.
15	Basin type double slope solar still with different wick materials [20].	The productivity is higher when light black cotton cloth is used as spread material.	It requires regular replacing of wick materials.
16	Single basin double slope solar still with thin layer of water in the basin [19].	The productivity is higher when light black cotton cloth is used as spread material.	Additional requirement of and 2KW electrical heater for heating the basin water and requires regular replacing of wick materials.
17	Effect of using gravel in the basin as an energy storing materials [36].	By using 20–30 mm size black gravel, the still productivity is increased by 19%.	More economical compared to other sensible heat storage materials.
18	Single basin solar still with energy storing materials [21].	Among the energy storing materials, 3/4" sized quartzite rock is the effective basin storage material.	Actual temperature of water and glass, production rate shows higher deviation with theoretical values due to the non-inclusion of higher proportion of water vapor in the air inside the still, effect of change in evaporative area and absorptivity of the materials used in the basin.
19	Stepped solar still with paraffin wax as storage medium [42].	Total productivity of the still is 4.6 L/m <sup>2</sup> with 57% efficiency.	Compared to sensible heat storage materials Paraffin wax gives higher yield.
20	Single basin solar still with PCM as a storage medium [43]	Total productivity of the still is 9.0051 L/m <sup>2</sup> /day with a daily efficiency of 85.3% compared to conventional solar still productivity of 4.9981 L/m <sup>2</sup> /day.	Compared to sensible heat storage materials PCM gives higher yield.
21	Solar still with aluminum black painted plate over the water temperature [48].	At 2 cm of water layer, black painted aluminum plate increases the efficiency by 28%.	The aluminum black painted plate and the thickness of the layer affect the productivity.
22	Solar still with black coated sheet floating over the water surface [49].	The productivity of the still is increased by 43%.	Higher water depth produces more output because of surface heating technique.
23	Single basin solar still with mica plate as a suspended absorber [50].	The daily productivity of the still is 42% higher than that of conventional solar still.	Mica is cheaper and corrosion free.
24	Solar still with floating perforated aluminum black plate as a surface heating technique [51].	At 3 cm brine depth, the efficiency of the still is 15% and at 6 cm brine depth, the efficiency of the still is 40%.	Higher water depth is high it produces more output because of surface heating technique.

the glass cover to atmosphere which results in increasing the solar still productivity [1].

Zurigat et al. [15], Rajvanshi [24], Garg et al. [63], Cooper [64], Soliman [65], Malik et al. [66] and El Sebaï [67,68] reported that

increase in wind speed produce higher productivity. Elbling et al. [69], Hollands [70] and Yeh et al. [71,72] reported that increase in wind speed results in higher productivity. Morse et al. [73] reported that the productivity of solar still does not depend on

**Table 2**

The various research work done on solar still to improve the condensation rate.

Sl. no.	Experimental work done	Performance of the still	Remarks
1	Performance of a solar still with water flowing over the glass cover [56].	The daily production of the solar still is almost doubled.	Temperature of flowing water over the glass cover and glass temperature are always nearly equal.
2	Effect of heat capacity on the performance of solar still with water flow over the glass cover [72].	Flowing water over the glass cover reduces the glass cover temperature as well as water temperature.	At large heat capacity of water mass in the basin the water flow over the glass cover is most effective.
3	Performance of Solar still with water film cooling of the glass cover [60].	By using film cooling the efficiency of solar still is increased by 6%.	Poor combination of film cooling leads to reduction in solar still efficiency.
4	Solar still with hemispherical top cover with and without flowing water over the cover [61].	The efficiency is 34% without top cover cooling and 42% with top cover cooling.	Poor combination of cover cooling leads to reduction in solar still efficiency.
5	Regenerative solar still with provision of cooling water to flow in and out of the second effect [15].	The productivity of regenerative solar still is 20% higher than conventional solar still.	The thickness of water on top of the first glass cover and the mass flow rate of water going into the second effect have marginal effect on the productivity of the regenerative still.
6	Effect of wind speed on passive solar still [69].	Minimum depth of water with high wind speed gives higher productivity of the still.	$P_d$ increases with increase of $v$ up to a typical velocity $V_c$ . For basin water masses less than the critical mass $P_d$ is found to decrease with increasing $v$ until $V_c$ .
7	Effect of wind speed on regenerative and conventional solar still [15].	The productivity of solar still is increased by 50% if the wind speed is increased from 0 to 10 m/s. Increase in wind speed increase the productivity of both regenerative and conventional solar still.	Perfect insulation increases the productivity of still up to two and one half folds.

wind speed. The reason for less amount of productivity is the temperature difference between glass cover and water. At higher wind speed the heat transfer from glass cover to atmosphere is high and the basin water is low. This makes the temperature difference between glass cover and basin water low, reducing the heat transfer rate and hence productivity.

El Sebaï [67] found the effect of wind speed  $V$  on the daily productivity  $P_d$  of the still. The Fig. 33 shows that with minimum depth of water and high wind velocity, the productivity of still is increased.

Zurigat et al. [15] found that wind speed has a significant effect on the productivity of the stills and it can increase the productivity by more than 50% (Fig. 34), incase if the wind speed is increased from 0 to 10 m/s. Increase in wind velocity increase the productivity of both conventional and regenerative solar still.

## 5. Conclusion

As a result of the above revision of a passive solar still, the different methods and modifications used to improve the rate of evaporation and condensation are listed in Tables 1 and 2 respectively.

### 5.1. Suggestions for the scope of future research work in passive solar desalination

It is suggested that the use of low thermal conductivity material as (for) basin and also placed thermal storage material in the basin improves the still productivity, because it does not easily allow the heat to the atmosphere which also simultaneously reduces the bottom heat losses.

By increasing thermal conductivity of water, the absorption rate of solar radiation is increased. For achieving higher thermal conductivity nano-fluids are used. Suspended nano-particles increase the surface area, the heat capacity of the fluid and also increases thermal conductivity of the fluid.

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